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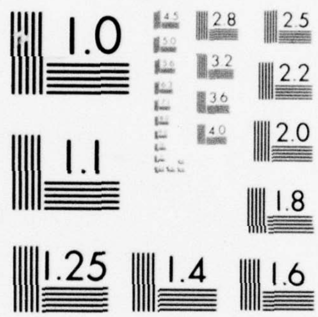

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AT THE INTERFACE OF MODELING AND ALGORITHMS RESEARCH

BY

G.B. DANTZIG AND S.C. PARIKH

TECHNICAL REPORT SOL 77-29

OCTOBER 1977

Systems Optimization Laboratory

Department of Operations Research

Stanford University

Stanford California 94305

AT THE INTERFACE OF MODELING AND ALGORITHMS RESEARCH†

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G.B. Dantzig and S.C. Parikh

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SYSTEMS OPTIMIZATION LABORATORY
DEPARTMENT OF OPERATIONS RESEARCH

Stanford University
Stanford, California

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Abstract

This paper looks at the efforts of the PILOT Modeling Group and the Solution Methods Group of Stanford's Systems Optimization Laboratory (SOL) and provides a presentation that describes some of the synergistic interactions that permit each effort to benefit in a substantive way from the day-to-day problems and the accompanying experience of the other. These efforts are beginning to complement in an important way the essential research activity of the other. Areas covered include model modifications in the PILOT System brought about by the computational realities and an outline of the work on testing algorithms for solving large-scale systems using PILOT.

AT THE INTERFACE OF MODELING AND ALGORITHMS RESEARCH

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I. Introduction and Summary

The Systems Optimization Laboratory (SOL) of the Department of Operations Research at Stanford is divided into Solution Methods (algorithms and software development) and Modeling Groups. The functions of the former are concerned with

(1) development of experimental software for solving large-scale dynamic systems, general mathematical programs, equilibrium and fixed point solutions, etc.,

(2) systematic comparison of proposed techniques on representative models,

(3) recording and dissemination of information regarding experimental results.

The Modeling activity of SOL is concerned with

(1) performing modeling and methodology research dealing with construction, solution, and interface of representative large scale mathematical programming based planning models of energy-economic systems that emphasize the role of energy and account for water scarcities and environmental impacts,

(2) using the modeling research towards performing analyses that provide insights into some of today's important public policy issues, and

(3) using the modeling and methodology work for construction of better models for improved analysis of tomorrow's important policy questions.

At the core of the modeling activity is the PILOT Energy Modeling Project directed at the development and use for policy analysis of a multi-sector intertemporal linear programming model of the U.S. Economy and an associated system of satellite models capable of providing disaggregation and assumption verification. The main model describes in physical flow terms many of the technological interactions within and across the sectors of the U.S. Economy and contains a detailed description of the U.S. energy sectors. The general aim is to permit studies (i) to assess how specific energy policies will affect the energy supply/demand picture, and (ii) to assess how the physical capacity of the economy over the next 30-35 years to provide goods and services to its populace could be affected by changes in the energy supply picture. By its very nature the project also deals with methodological and formulational research to build dynamic growth and welfare equilibrium models that emphasize the role of energy and with research on efficient computational solution of such models. In latter regard, the PILOT project is in a unique position to benefit from the activity of the Solution Methods Group of the Systems Optimization Laboratory on development and testing of solution algorithms for large-scale mathematical programming systems.

The purpose of this paper is to provide a presentation that describes some of the synergistic interactions that permit modeling and algorithms efforts to benefit in a substantive way from the day-to-day problems and the accompanying experience of each other. These efforts are beginning to complement in an important way the essential research activity of the other. The PILOT modeling effort furnishes important test problems on which to focus a significant portion of SOL's research on development and implementation of algorithms for solution of large-scale systems. On the other hand, the computational experience of the algorithm developers at SOL and elsewhere is seen as an important source of ideas in keeping the components of PILOT Modeling System manageable from the computational standpoint. As we shall see in the sequel, some of the important changes in the component size and detail reflect computational realities.

II. The Mid-1976 PILOT--A Summary Description

Our earlier modeling activity for PILOT concentrated on the supply side of the energy picture [1]. Activities that provide useful energy to the economy constitute the detailed energy submodel. It consists of technological descriptions of the raw energy extraction and the energy conversion processes as well as the energy import and export activities. Details of this submodel include the modeling of oil and gas exploration and extraction, uranium extraction, new technologies for conversion of fossil fuels, and the nuclear fuel cycle.

In a less detailed way the model includes a description in physical terms of the other industrial processes of the economy, the final demands for consumption, capacity formation, government services and net exports, and the foreign trade balance relationships. A dynamic input-output system is employed to describe growing industrial activity. The temporal profile of the labor force and its productivity are assumed given.

Four linkages interconnect the energy sector to the rest of the economy: energy demands of the economy, goods and services needed for energy processing and capacity expansion, total manpower available to all sectors (including energy), and a trade balance constraint.

The industrial sectors of the economy are represented by a 23 order input-output matrix (Exhibit 1). The sectors are grouped as follows: 5 energy sectors, 1 agriculture, 1 nonenergy mining, 5 energy intensive manufacturing, 4 energy nonintensive manufacturing, 4 services, and 3 capital formation. For computational efficiency, a modification was implemented that permits automatic aggregation to a 12 sector detail. A comparison of computation related statistics is given in Section 3. In the aggregated version, five energy sectors are preserved but nonenergy sectors are aggregated into the following seven sectors: agriculture, mining and construction, energy intensive manufacturing, energy nonintensive manufacturing, transportation, services, and machinery and transportation equipment.

SIGMA MODE (12 SECTORS)			STANDARD MODE (23 SECTORS)		BEA SECTORS (87 INDSTRL. SECTORS)
LINE COUNT	SECTOR CODE	SECTORS	SECTOR CODE	LINE COUNT	INDUSTRY NUMBER
		MACROENERGY SECTORS			
1	COL	Coal	COL	1	7
2	CRO	Crude Oil and Crude Natural Gas	CRO	2	8
3	ROP	Refined Oil Products	ROP	3	31
4	GAS	Gas	GAS	4	68.02
5	ELE	Electricity	ELE	5	68.01,78.02,79.02
		MACRO NONENERGY SECTORS			
6	AGR	Agriculture	AGR	6	1-4
7	MNG	Mining and Construction			
		Mining	MNG	7	5,6,9,10
		Construction	CON	8	11,12,55
8	EIM	Energy Intensive Manufacturing			
		Chemicals and Plastics	CMP	9	27-30,32
		Foodstuffs	FDS	10	14,15
		Paper Products	PPP	11	24,25
		Stone, Clay, and Glass	SCG	12	35,36
		Primary Metals	MET	13	37,38
9	ENM	Energy Nonintensive Manufacturing			
		Textiles, Leather, Clothing, and Shoes	TEX	14	16-19,33,34
		Lumber	LUM	15	20
		Furniture and Appliances	FAP	16	21-23,54
		Miscellaneous Manufacturing	MFG	17	13,26,39-42,56, 57,62-64
10	TAW	Transportation and Warehousing	TAW	18	65
11	TRD	Trade and Other Services			
		Wholesale and Retail Trade	TRD	19	69
		Finance and Real Estate	FIN	20	70,71
		Miscellaneous Services	SVS	21	66,67,68.03,72, 73,75-79 (except 78.02,79.02),81-87
12	MAC	Machinery and Transportation Equip.			
		Transportation Equipment	TRE	22	59-61
		Machinery	MAC	23	45-53,58

Exhibit 1. Sectoral Aggregations of PILOT

Consumption is modeled in terms of consumption patterns of the average consumer. This sector does not have a fixed bill of goods; the consumption vector varies linearly as a function of a parameter representing the total per capita consumption attained. Details of these consumption functions can be found in Avriel [2].

Capital formation needed for replacement of retired plant and equipment as well as for capacity expansion is endogenously modeled.

Exports are treated endogenously as final demand items. The imports are also considered endogenously. Finally, the trade balance constraint requires that the costs of imports not exceed the revenues from exports when these items are evaluated in terms of 1967 dollars over each five year period.

The detailed energy sector contains conventional energy technologies such as oil refineries, coal fired power plants, etc., as well as new technologies of the future such as coal synthetics, oil shale, plutonium recycle reactors, etc. (Exhibit 2). The energy sector also includes a description of the exhaustion process of the three exhaustible energy resources: oil, gas, and uranium through activities of oil and gas exploration and production, and uranium extraction.

The maximand in the mid-1976 PILOT is the undiscounted sum of the gross national consumption over forty years subject to (i) a "monotonic per capita consumption" constraint, requiring that the average per capita consumption must be non-decreasing over time, (ii) an initial condition stating a lower limit on the first period consumption, and (iii) a terminal condition stating a lower limit on the amount of capital formation in the last period.

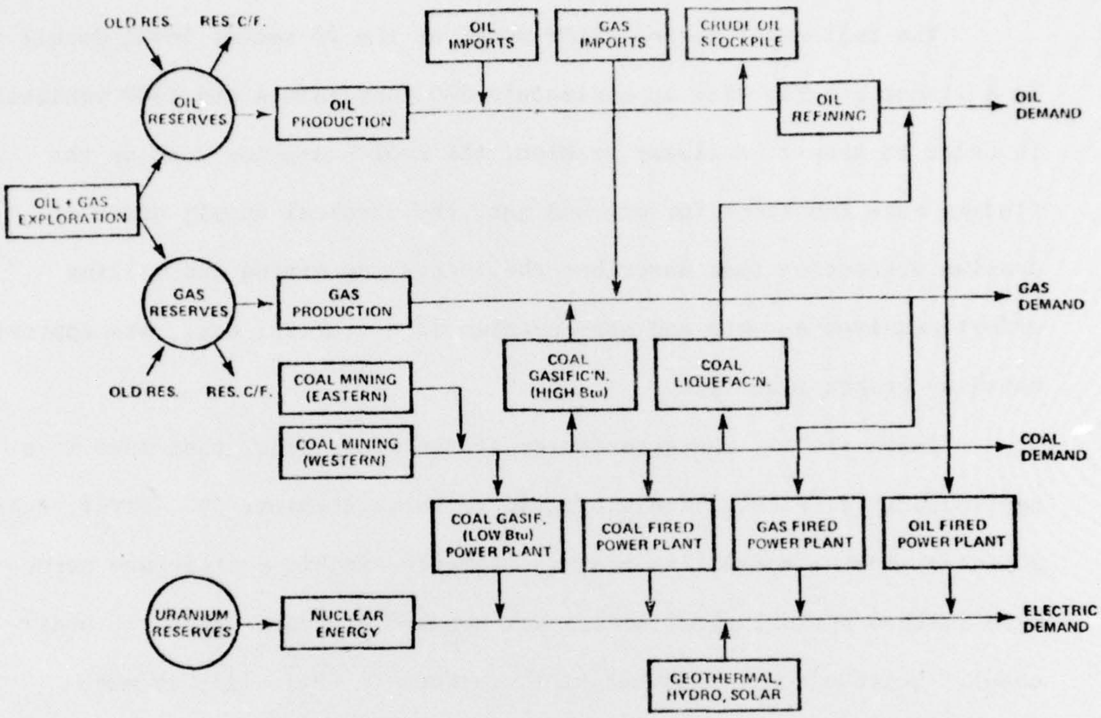

Exhibit 2. The Energy Sector of PILOT

III. Computer Solution of the PILOT Model

The full eight period PILOT model at the 23 sector level detail is a linear program with approximately 900 constraints and 1900 variables. In order to keep it a linear problem, the nonlinearities such as the finding rate functions for oil and gas, the physical supply curve of uranium extraction that describes the increasing mining and milling effort required as more and more uranium is extracted, etc., are approximated by broken line fits.

There are two characteristics of the PILOT model that make it a particularly difficult linear program to solve (Exhibit 3). First, being an intertemporal model, its nonzero elements exhibit a staircase structure (with a sprinkling of additional nonzero elements below the staircase). Quite often the number of iterations to optimality is much larger than the usual thumb rule of two to three times the number of rows. In our computations, the iteration count varies anywhere from six to twelve times the number of rows, with actual multiple depending upon the particulars of the scenario being developed and (mostly accidental) availability of an "advanced" basis. Other people who have solved dynamic optimization systems report similar experience.

The second characteristic that poses a significant difficulty concerns the presence of the dense (almost all nonzeros) input-output matrix, in the matrix block for each time period. In the 23 sector version of the PILOT model, approximately 500 nonzero elements appear in the 23 × 23 block in each period. This dense block increases the computational effort needed per iteration.

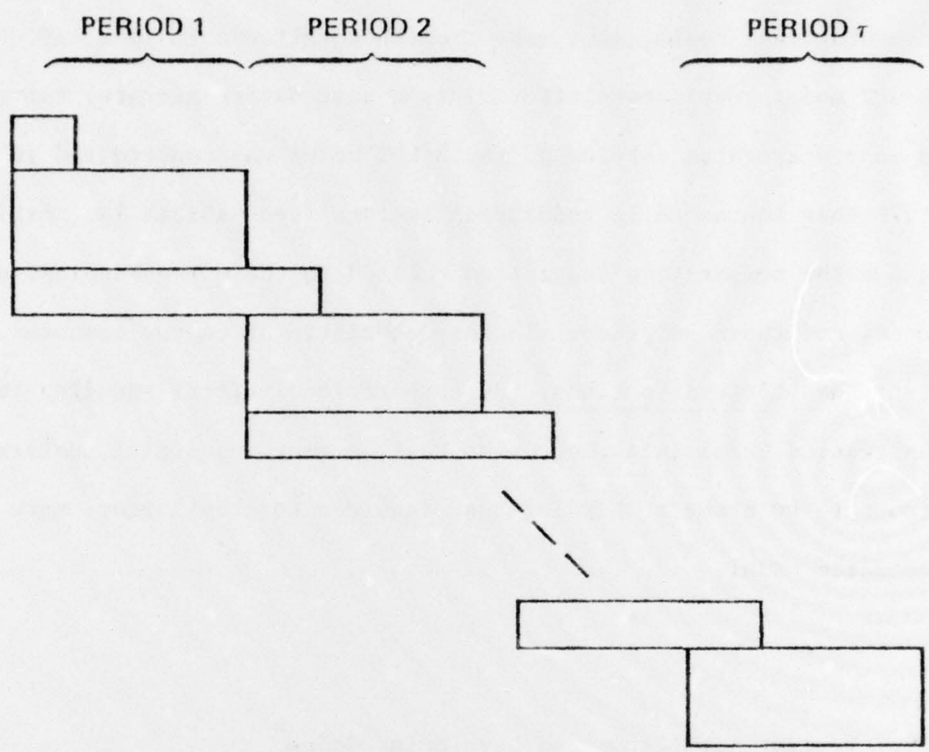

Exhibit 3. The Dynamic Staircase Structure of PILOT

(Actual matrix has a sprinkling of non-zeros below the non-zero blocks.)

The net result of the above two characteristics was significant computational costs, much more than those affordable in a university based model development effort. As a cost saving measure, therefore, a more aggregated version of the PILOT model was constructed in late 1976 that contained 12 industrial sectors (see Exhibit 1). Exhibit 4 shows the comparative statistics related to these two versions of the model and their solution. The key statistic of course concerns the fact that, ceteris paribus, the computational effort required for the aggregated model (with more than half as many industrial sectors) was found to be about a third of that required for the larger, more disaggregated model.

IV. Testing Algorithms and Developing Codes*

Work on testing several ideas on efficient solution of large-scale staircase models continues at the Systems Optimization Laboratory. These tests are now being performed using a version of the PILOT Model.

In broad terms two main approaches to improved computational efficiency are being pursued at SOL: (I) improving the solution path or (II) speeding up the computation in each step of the simplex algorithm while following the same solution path.

---

*This section based on summary prepared by J.A. Tomlin.

	Standard Mode	SIGMA Mode
Original		
Rows	910	713
Columns	1856	1328
Elements	12550	7392
Density	.49	.50
Whizard		
Rows	807	620
Columns	1807	1274
Spikes	195	118
Bump Cols	573	366
Bumps	7	10
initial ETA non-zeros	22553	7659
Computational Effort		
Approx. # iterations in a 2 min. run	200	600
# iterations to optimality from cold start	6500-9000	5000-7000
CPU minutes to optimality from cold start	60-80 min	20-25 min[†]
Additional cases	10-20 min	3-7 min
Storage Requirements		
Matrix on 2314 disc	95 tracks	58 tracks
Basis on 2314 disc	11 tracks	8 tracks

(All figures should be viewed as approximate. Some of them vary within and across optimizations.)

[†] Better scaling and other measures designed to exploit the capabilities of the MPS3 System have recently reduced the computational effort to 10-15 minutes.

Exhibit 4. Comparative Statistics of the PILOT Model in Standard and SIGMA Mode (December 1976)

A promising method for reducing solution time for dynamic models involves several modifications to the simplex method designed to take advantage of the special properties and behavior of such models. One property of interest is a tendency of the same type of activity to be basic over several successive time periods. It therefore seems desirable to introduce simultaneously a profitable type of activity in as many time periods as possible. M.A. Saunders and J.A. Tomlin have explored variants of the reduced-gradient method for nonlinear programming algorithm adapted for linear problems to change several nonbasic variables simultaneously (in contrast to the standard simplex method which changes only one nonbasic variable at a time). For this purpose they modified MINOS software package developed by Murtagh and Saunders [3]. To ensure that the correct nonbasic variables are used, a "special pricing" technique is employed. When the problem is read in, similar activities in different time periods are identified (from column or variable names) and linked by a circular list. Thus when an activity is priced out and found to have a favorable gradient, the corresponding vectors in other time periods can be easily found and examined, and if satisfactory, included as candidates to be changed. It is then possible to make a step which introduces an activity in several successive time periods simultaneously.

Preliminary experiments with the above approach have led to a reduction of 20-30% in Phase II iterations when compared to the standard simplex method applied to the type of economic planning models referred to above. It is clear that many tactical variations of the scheme need to be studied.

If it is advantageous to bring in an activity simultaneously in many time periods, then conversely, it should be advantageous to be able to also force an unprofitable activity to its lower bound in several time periods simultaneously. This is rather more difficult, since one cannot tell whether a whole group of variables can reach their bounds while maintaining a feasible solution (at least, not without incurring a heavy computational cost). Many selection rules are possible, and considerable experimentation is required to refine the methodology.

Another means of improving solution time for staircase models is to speed up each step of the simplex algorithm by taking advantage of the special structure of the basis for such problems. As early as 1954, one of us [4] pointed out that such problems exhibit an "almost" square block-triangular basis structure which could be decomposed into a product of a true square block-triangular matrix and another matrix with only a few columns differing from the unit matrix. The advantage of this procedure is that square block-triangular matrices can themselves be very efficiently decomposed to give a very sparse factorization of the basis. A version of this method, employing modern factorization techniques, has been implemented at SOL by A.F. Perold and is now being tested using the PILOT model [5]. Early indications are that this method of handling the basis can be more efficient than a direct treatment which does not take the staircase structure of models into account.

Several years ago James Ho and Alan Manne and independently Roger Glassey proposed solving staircase structures by means of a nested decomposition approach [6,7]. This research is continuing in our Systems Optimization Laboratory and at Brookhaven National Laboratory under James Ho, Larry Nazareth, and M. Aganagic. Again the results are promising. In both approaches outlined above there have been improved efficiencies on the cases tested so far but the improvements are not sensational. We have also encountered problems of stability occasionally which may be more the result of an unlucky choice of test cases than a weakness of the methods. Work is continuing.

In passing, it might be noted that the modeling activity often provides the algorithm developers a <u>user catalyst</u> that can facilitate identification and promote implementation of some of the use features that make the computer codes easy to use and compatible with other available software. In this vein, use of MINOS in PILOT computations has played a significant role in identification of some of the needed features and options in MINOS that improve its usability. Current MINOS code is compatible with MPS3, for example. It is now possible to switch back and forth between MINOS and MPS3 during a given optimization calculation without any special data processing. This opens up a possibility of some research on identification of switching rules to exploit the strengths of these two codes.

V. Welfare Equilibrium Variant of PILOT

One of the main weaknesses in the mid-1976 PILOT is that it does not contain explicit modeling of the substitution possibilities on the energy demand side. Thus, the possibilities of switches by the consumers and the industry from the scarce forms of fuels to more abundant forms of fuels, labor, and capital are not endogenously considered in the model.

Efforts to incorporate explicit modeling of the substitutions on the energy demand side lead one to the difficult but challenging problems of building general or market equilibrium systems. Work briefly reported below of one of the authors on identification, construction, and solution of such systems is well along. See Parikh [8,9]. A survey of the other efforts is beyond the scope of this paper. We briefly note however that (i) large problems with linear demand functions can be handled as quadratic programs, (ii) small to intermediate size nonconvex problems (perhaps up to 50 variables or so) can be formulated and solved using fixed point methods being investigated by Eaves [10,11], Engels [12], Saigal [11,13], Scarf [14], and others, and (iii) heuristic approaches sometimes work well for large and possibly nonconvex problems as demonstrated in the computer solution of the Project Independence Evaluation System.*

As noted, work is continuing to develop a variant of the PILOT model that permits its operation in a welfare equilibrium mode. In this variant, computation of an economic equilibrium involves solution of one or more linear programs.

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*Work to obtain theoretical results on convergence is currently being performed by B. Ahn, a graduate student, under the supervision of W.W. Hogan.

The essential change in implementation of this formulation concerns the incorporation of endogenous substitution possibilities through sectoral production functions for nonenergy sectors of the dynamic input/output system and through a social utility function for the consumption portion of the final demand. The net result is a replacement of the 12-sector fixed coefficient input/output system by a more flexible production system and a characterization of the substitution effect in the consumer demand in addition to the income effect extant in the mid-1976 PILOT model.

The key modeling concept in this formulation is use of hierarchical homothetic functions or such functions with displaced origin of coordinates. These functions permit representation of substitutions through a hierarchical structure where at each level in the hierarchy the entire set of variables is partitioned into subsets and substitutions across variables in a given subset are considered independently of the actual levels of the variables from any other subset. This method of approximating a more general form of substitutions is intuitively appealing since it allows one to consider the total maze of substitutions in small and managable subgroupings. While the general approach allows for consideration of substitutions across three or more variables or their aggregates at a time, it is used in the Welfare Equilibrium Variant in a simplified form in which the substitutions across only a pair of variables or their aggregates are considered at any point in the hierarchy. For example, between leisure and material things, and then say, within the material level between energy and nonenergy items, etc.

The key computational advantage of hierarchical homothetic functions is that each pair can be approximated by a broken line fit to a curve. The number of variables and equations needed for the approximating fits is additive in the number of pairs instead of exponential in the number of variables in the function.

When the changes for implementing the Welfare Equilibrium Variant are incorporated in the PILOT model, the economy part of the model becomes a 'flexible energy demand generator'. The PILOT model can now be viewed either in terms of welfare maximization (through maximization of social utility) or market equilibrium.

In the later view, it is important to note that the primal part of the linear program deals only with the quantities and it is the dual problem that characterizes the market prices by equating them to marginal utility and marginal costs. Thus, the consumer demand functions are not explicitely represented as in other models but are determined implicitly through the utility function.

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